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(Research Article)

Calculation of thermal efficiency of the upper convective zone of a solar pond device

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Abstract

Solar pond technology is an effective and most economical way to convert and store solar thermal energy. In this paper, numerical and experimental studies were conducted to investigate the energy distribution and efficiency in the inner zones of an inverted truncated pyramid shaped solar pond. For this purpose, a small-scale solar pond was built and tested at Karshi State Technical University. The height of the solar pond is 1.5 m, the lower and upper bases are 0.7 m and 1.5 m, respectively. The volume is approximately 2 m3.

Keywords: Solar pond; Solar radiation; Concentration; Energy efficiency; Upper convective zone; Lower convective zone

1. Introduction

In recent years, both developed and developing countries have been increasingly focusing on expanding the share of renewable energy sources in their energy supply systems and adopting environmentally friendly methods for electricity generation, as part of efforts to develop a green economy. Among renewable energy sources, solar energy is the most widely used. There are many devices that utilize solar energy, and solar ponds can be used to collect and store this energy [1-2]. The performance of a solar pond largely depends on the amount of solar energy it receives and the extent of heat loss from the pond. Solar energy is derived from incident solar radiation, which is converted by the solar pond into useful thermal energy. As solar radiation penetrates deeper into the pond, it gradually dissipates, and its radiant energy is absorbed by the various layers of the pond. The energy accumulation processes of solar ponds have been studied by numerous researchers around the world. In this regard, Tunisian scientists Ridha and Mounir analyzed the operation of a solar pond by digitally studying salinity gradients and heat and mass transfer within the pond [3]. Researchers such as Liu, Jiang, and others explored the characteristics of a trapezoidal solar pond using digital modeling methods, taking into account water concentration and turbidity [4]. Karakilcik investigated the thermal performance of surface solar ponds, specifically examining energy and exergy efficiency [5]. Kayali and colleagues developed empirical functions for temperature variation and energy efficiency of a rectangular solar pond based on underground soil temperature and two-dimensional heat balance equations [6]. Spanish researchers Bernad and others developed a digital model based on the overall energy balance of a pond to study the energy efficiency of a solar pond in an industrial process, considering thermal storage efficiency [7]. Today, the thermal energy generated from solar ponds is actively used for various purposes, including heating buildings, generating electricity, transferring thermal energy for industrial processes, and supporting several other applications.

2. Material and methods

When sunlight reaches the surface of the water, a portion of it is reflected back into the sky. The long-wavelength components of solar radiation are mainly absorbed by the upper convective zone, while the short-wavelength components are absorbed by the lower convective zone (Figure 1).

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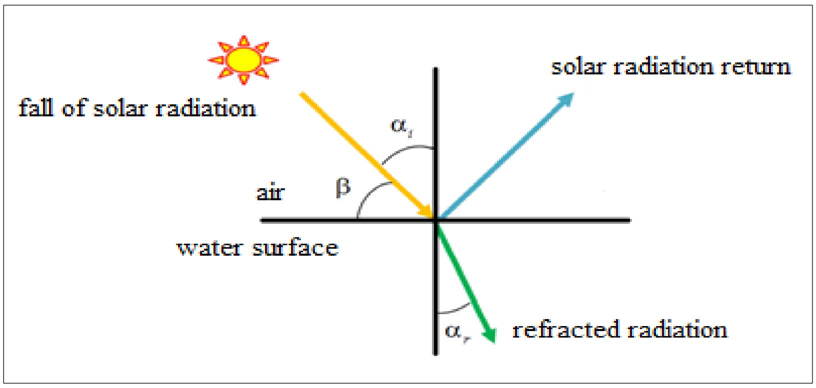

Figure 1 Reflection and refraction of solar radiation

To calculate the incident radiation flux on the surface of a solar pond and the radiation flux absorbed within the pond, one can use the formula proposed by British scientists Bryant and Colbeck [5]..

$$\frac{Q_x}{Q_o} = \left\{ 0,36 - 0,08 \ln\left(\frac{x}{\cos\alpha_r}\right) \right\} \qquad \text{..................(1)}$$

Where Q_o -the insolation on a horizontal surface, while Q_x - the radiation flux at depth x, α_r -the angle of refraction of the radiation entering the pond [5].

The refraction of solar radiation at the air–water interface can be expressed as follows [6]:

$$\frac{\sin\alpha_i}{\sin\alpha_r} = \frac{n_r}{n} = 1,333 \qquad \text{............(2)}$$

Where n -the refractive index of air, n_r - the refractive index of water, and α_r - the angle of direct solar incidence relative to the normal to the horizontal plane.

Solar rays can penetrate several meters into the water depending on its transparency and clarity. Therefore, it is important to keep the water clean.Q_{evap}

The middle layer of a solar pond acts as a thermal insulator, preventing the loss of energy accumulated in the bottom layer. The efficiency of a solar pond depends on its capacity to store thermal energy and the cost of construction. Therefore, accurately analyzing its heat balance is considered essential. The thermal balance of a solar pond can be established by developing a mathematical model for each of its zones (Figure 2).

The amount of energy received by each layer, the radiation energy absorbed by the layer, the energy lost from the layer, and the accumulation of energy over time within the layer must be equal. An energy balance is formulated for each zone of the solar pond, including the upper convective zone (UCZ), the non-convective middle zone (NCZ), and the lower convective zone (LCZ), for each time interval of the model. The energy balance for the UCZ layer, based on the principle of energy conservation, is expressed as follows.

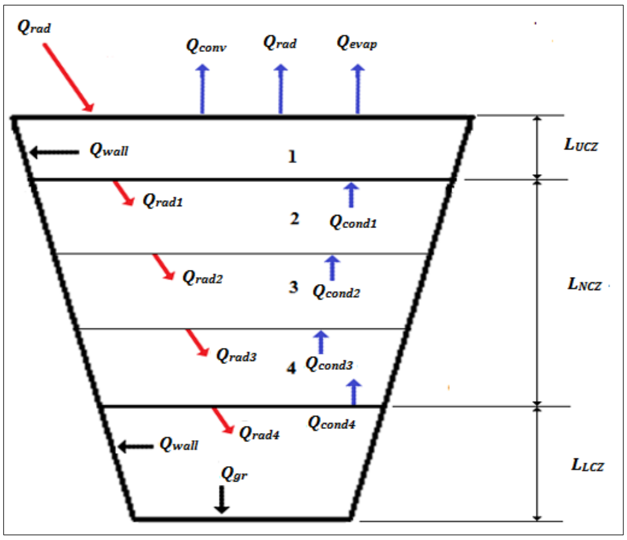

Figure 2 Thermal balance model of the solar pondFigure

Heat losses from the surface of a solar pond significantly affect its overall performance. These heat losses occur due to evaporation, radiation, conduction, and convection processes. Although the solar pond serves as a heat source, studies have shown that its surface temperature is approximately 3–5% lower than the ambient air temperature [7].

A summary of the heat absorption and heat loss values in the upper zone of the solar pond is illustrated in Figure 3.

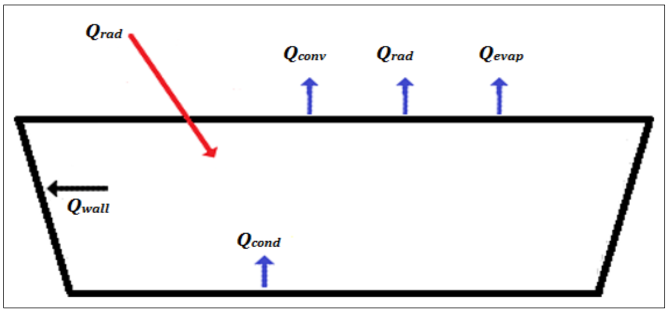

Figure 3 Heat balance of the upper zone of the solar pond

In the upper zone of the solar pond, heat is absorbed due to solar radiation and heat transfer from the lower zone. However, a certain portion of this heat is lost through the four processes mentioned above.

The heat balance equation for the upper zone of the solar pond can be mathematically expressed as follows:

$$Q_{ucz} = Q_{rad} + Q_{cond} - Q_{evap} - Q_{total} - Q_{wall} \quad \text{..................(3)}$$

Where:; Q_{rad} - heat absorbed from solar radiation in the upper zone [W],, Q_{cond} - heat received from the bottom layer [W], Q_{evap} - heat loss due to evaporation [W], Q_{total} - total heat loss from the surface of the solar pond to the surrounding environment [W], Q_{wall} - heat loss through the side walls of the solar pond [W].

Solar energy incident on the surface of the upper zone of the solar pond.

$$Q_{rad} = \alpha \tau F_{ucz} q_{rad} \quad \text{..............} \quad (4)$$

Where:, τ - transmission coefficient of the transparent surface of the upper zone of the solar pond, α - absorption coefficient of the upper zone, F_{ucz} -surface area of the upper layer of the solar pond [m^2], q_{rad} - intensity of solar radiation [W/m^2].

Heat energy obtained from the lower layer of the solar pond

$$Q_{cond} = \frac{\lambda_{ucz} F_{nkz}}{L_{ucz}} (t_{nkz} - t_{ucz}) \quad \text{..................(5)}$$

Where: t_{ncz} - temperature of the middle layer of the solar pond, [°C]; t_{ucz} - temperature of the upper layer, [°C]; λ_{ucz} - average thermal conductivity of the upper layer, [W/m·K]; F_{ncz} - surface area of the middle layer of the solar pond, [m^2]; L_{ucz} - thickness of the upper layer, [m].

Compared to other forms of heat loss, evaporation from the surface of the solar pond results in a significantly larger amount of heat loss.

According to the VDI 2089 standard formula by the Association of German Engineers, the heat loss due to evaporation from the total surface area of the upper layer of the solar pond is given as follows [8]:

$$Q_{evap} = W \cdot r = \varepsilon F (P_{vp} - P_{pvp}) \cdot r \quad \text{................(6)}$$

Where: F- surface area of the water in the upper layer of the solar pond, [m^2]; P_{vp} - vapor pressure of saturated air at the water temperature in the pond, [Pa]; P_{pvp} - partial vapor pressure of water in the ambient air (based on surrounding temperature and humidity), [Pa]; ε - empirical coefficient, $\varepsilon = 5$ [g/m^2·h·bar]; r - latent heat of vaporization of water at a given temperature, [kJ/kg] [8].

The total heat loss from the surface of the upper layer of the solar pond to the environment through convection and radiation can be calculated using the following formula.

$$Q_{total} = (\alpha_{conv} + \alpha_{rad}) F_{ucz} (t_{ucz} + t_a) \quad \text{................(7)}$$

Where α_{conv} - convective heat transfer coefficient, [W/m^2·K]; α_{rad} - radiative heat transfer coefficient under solar radiation, [W/m^2·K]; t_a - ambient air temperature, [°C].

To calculate the convective heat transfer coefficient, the equation provided by McAdams [9] can be used.

$$\alpha = 5.7 + 3.8 w_{air} \quad \text{...............(8)}$$

w_{air} - air velocity above the surface of the solar pond water.

In calculating the energy balance of the upper layer of the solar pond, heat loss through the side walls of the upper layer is considered significant. It can be calculated using the following formula:

$$Q_{wall} = \frac{F_{wall}}{R} (t_{ucz} - t_a) \quad \text{...............(9)}$$

Where: F_{wall} - surface area of the side walls of the upper layer of the solar pond, [m^2]; R -qthermal resistance of the pond wall, [m^2·°C/W].

Considering the first law of thermodynamics, the heat efficiency of the upper zone of the solar pond can be expressed as follows:

$$\eta_{ucz} = \frac{Q_{ucz}}{Q_{ret}} \qquad \text{.....................(10)}$$

The heat retained in the upper convective zone can be calculated in the following form.

$$Q_{ucz} = Q_{ret} - Q_{loss} = (Q_{rad} + Q_{cond}) - (Q_{evap} + Q_{total} + Q_{wall}) \qquad \text{..............(11)}$$

Now, by substituting equation (10) into equation (11) for the upper convective zone, the energy efficiency of the UCZ (Upper Convective Zone) can be calculated using the following empirical formula.

$$\eta_{ucz} = 1 - \frac{Q_{rad} + Q_{cond}}{Q_{evap} + Q_{total} + Q_{wall}} \qquad \text{.................. (12)}$$

3. Results and discussion

The research work was carried out in September and October of 2023, within the concentration range of 25-27% NaCl salt solution in the solar pond. During the experimental work, the heat efficiency of the upper convective zone (UCZ) of the solar pond was measured for each month. The study determined the variation of the temperature in the UCZ of the solar pond over time and the average value of energy efficiency.

During the conducted research, it was determined that the energy efficiency of the UCZ of the solar pond was an average of 46% in September and 43% in October. The temperature of this zone rose to 32°C in September and 28°C in October, as can be seen from the graphs.

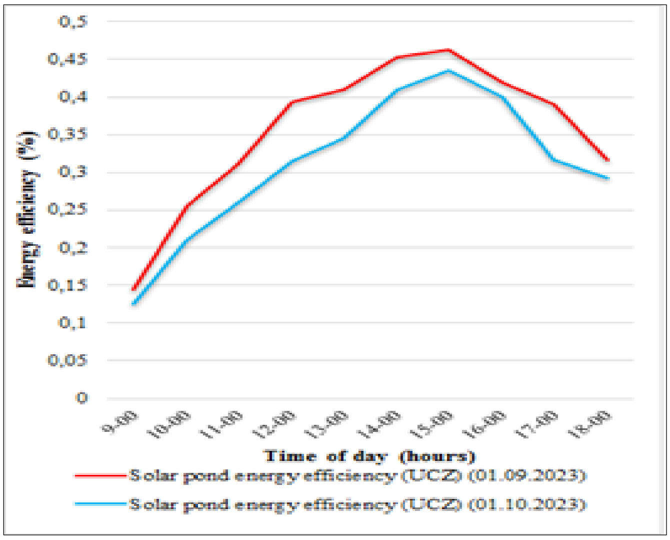

Figure 4 Energy efficiency graph of the UCZ of the solar pond device

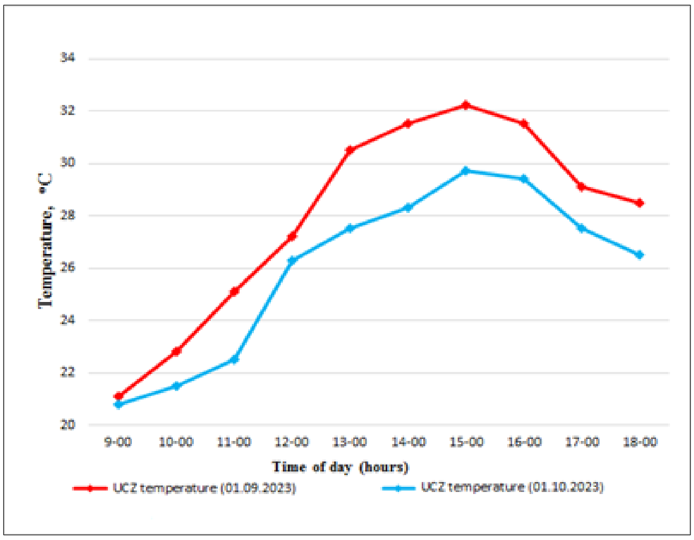

Figure 5 Temperature change graph of the UCZ of the solar pond device

4. Conclusion

The following conclusions were drawn from the analysis of the results of theoretical and practical research:

For a reliable, realistic, and scientific assessment of the performance of solar ponds, it is necessary to conduct a deep analysis of thermodynamic efficiency, including both energetic and exergetic approaches.

Solar ponds, especially in rural areas, are suitable for heat extraction processes without consuming electrical energy.

When calculating the efficiency of solar ponds, the turbidity of the water is an important parameter, and with the increase in turbidity, the efficiency of the pond decreases.

It was determined that the energy efficiency and temperature of the zones of the solar pond, including the upper convective zone, can increase or decrease depending on the solar radiation and environmental temperature

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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